Research Article

Received: 8 February 2011 Accepted: 8 June 2011 Published online in Wiley Online Library: 28 July 2011

(wileyonlinelibrary.com) DOI 10.1002/jsfa.4573

Relating raw rice colour and composition to cooked rice colour

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Abstract

BACKGROUND: The whiter the rice, the more it is preferred by consumers and the more value it has in the market place. The first objective of this study was to determine the interrelationships of raw colour, cooked colour, amylose content and protein content in rice. The second objective was to assess whether or not the colour of cooked rice can be predicted from raw rice colour in conjunction with amylose and protein contents.

RESULTS: Protein and amylose contents were not significantly correlated with the colour measurements for raw rice. Protein and amylose showed moderate, significant associations with *L and *a** and *a**, *b** and *C** respectively for cooked rice. Only the colour variable *a** of cooked rice could be predicted using protein, amylose and raw rice colour with high enough precision to be useful, and this was only for modelling using samples cooked in the same manner (rice cooker). Cooking method (rice cooker *versus* excess water) affected the colour of cooked rice.**

CONCLUSION: Being able to predict *a in cooked rice is likely of limited value. Only the model that used samples where postharvest handling conditions were controlled (US-grown rice) was able to predict *C**, a more useful measure, and then with only moderate ability. *L**, a measure of brightness/whiteness, was not predicted well by any of the models.**

Keywords: raw rice colour; cooked rice colour; amylose; protein

INTRODUCTION

Rice consumers, particularly from countries in which rice is the staple, have strong preferences for the sensory properties of rice. Different countries have different requirements for the flavour and texture of rice, and within countries a range of preferences can be found. However, when it comes to appearance, many consumers desire raw and cooked rice with a high degree of whiteness.[1,2]

Research has delineated some factors that affect the colour of raw and cooked rice. Lamberts *et al*.[3] observed that brightness (L^*) of raw rice kernels increased while redness (a^*) and yellowness (b^*) decreased until a degree of milling of approximately 15% (bran and outer endosperm removed). Further milling did not affect rice brightness. Levels of red and yellow pigments continued to decrease with milling until the middle endosperm was reached. L^* of cooked rice increased and a^* decreased until the degree of milling reached 9%, after which there was no change in these parameters. The b^* value of cooked rice decreased with degree of milling and continued to decrease with degree of milling above 9%. The decrease in yellowness and redness with increase in degree of milling was explained not only by loss of pigments but also by increased water uptake by the kernel, which resulted in lower pigment concentrations.

Jang *et al*.[4] reported that storage temperature is a major factor affecting the colour of milled rice, with the value of b^* increasing as storage temperature increased. Lee *et al*.[5] showed an increase in b^* of cooked rice as storage time of rough or milled rice increased from 1 to 3 years at 4 °C. They suggested that an increase in the b^* value of cooked rice was a result of Maillard reaction during storage. The effects of drying temperature, exposure duration and moisture content on the colour of milled rice have also been examined.[6] Exposure to temperatures above 45 °C caused an increase in colour intensity designated as chroma (C^*). Holding rice for 72 h at temperatures above 45 °C caused the hue angle to decrease, indicating that the rice became redder in colour. Yellowing of rice was minimized if rice was not exposed to temperatures above 50 °C for more than 12 h. Moisture content did not have a significant effect on yellowing.

Little attention has been given to relating raw rice colour to cooked milled rice colour and, specifically, to determining the influence of amylose and protein contents on cooked colour. Thus the first objective of this study was to determine the interrelationships of raw colour, cooked colour, amylose content and protein content in rice using a diverse set of premium, aromatic and non-aromatic cultivars from the USA and rice-growing countries around the world. The second objective was to assess whether or not the colour of cooked rice can be predicted from raw rice colour in conjunction with amylose and protein contents.

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MATERIALS AND METHODS

Samples

Twenty premium rice cultivars, sourced from the national programs of nine rice-growing countries around the world, were cultivated, dried and milled following established protocols for each cultivar. The details are reported in Champagne *et al.*[7] The cultivars were Zhongzheyou and Guodao 6 (China National Rice Research Institute, Hangzhou, China), Koshihikari and Koshiibuki (Niigata Prefectural Agricultural Institute, Niigata, Japan), IR 64, IRRI 1132, Sambha Mahsuri and Swarna (International Rice Research Institute, Los Banos, Philippines), Khao Dawk Mali 105 (KDML 105) and Pathumthani 1 (PTT1) (Ubon Rice Research Center and Patumthani Rice Research Center, respectively, Thailand), Pelde and Langi (Leeton Field Station of NSW Agriculture's Yanco Agriculture Institute, Yanco, NSW, Australia), BR IRGA 417, BRS Jacana and BRS Primavera (Palmital and Capivara farms of Embrapa Rice and Beans, Goias State, Brazil), Super Basmati and Basmati 385 (farmer's field and Kaku Rice Research Institute, respectively, Punjab Province, Pakistan) and Hashemi and Khazar (Iran). KDML 105 and PTT1 are jasmine cultivars, Super Basmati and Basmati 385 are basmati cultivars and Hashemi and Khazar are basmati types. The other cultivars are non-aromatic, with Samba Mahsuri and Swarna being characterised by having slender grains similar to the basmati types. The milled rice was shipped to the International Rice Research Institute (IRRI), Los Banos, Philippines, where it was fumigated for 72 h with phostoxin and then shipped to the USDA ARS Southern Regional Research Center, New Orleans, LA, USA via courier. The rice samples were stored under refrigeration at the Center until analysed.

Eight aromatic rice cultivars representing jasmine (Charleston Gold, Jasmine 85, Jasmine Early Short (JES), Jazzman), basmati (Aromatic se2, Dellmati) and della (Dellrose, Sierra) types were grown at the USDA ARS Rice Research Unit, Beaumont, TX, USA and the USDA ARS Dale Bumpers National Rice Research Center, Stuttgart, AR, USA. The rice cultivars were harvested during the first 2 weeks of September 2009, dried with a forced air drier to 120 g kg^{-1} moisture content in cloth bags and stored in a 4 °C cold room for 5 months. The Arkansas samples were shipped to the Texas laboratory and all samples were milled to the same level of whiteness using a Yamamoto VP-32T mill (Yamamoto Co., Higashine, Japan), with whiteness being measured using a Satake MM-1B whiteness meter (Satake Engineering Co., Tokyo, Japan). Milled samples were shipped to the USDA ARS Southern Regional Research Center, where they were stored under refrigeration until analysed.

Chemical analyses

Apparent amylose content in the samples was determined in duplicate by the simplified iodine assay method.[8] Protein content (N × 5.95) was determined in duplicate by the combustion method using a LECO FP-428 nitrogen determinator (St Joseph, MI, USA).

Sample preparation

The cooking protocol for each rice was typical of how the rice cultivar is cooked in its country of origin. Although there is no one preferred method for cooking rice in the USA, the rice cultivars grown in the USA were cooked in rice cookers.

Samples prepared in rice cookers

Portions (600 g) of milled rice were washed by covering the rice two or three times with cold water followed by straining to remove excess water. After washing, samples were transferred to preweighed rice cooker insert bowls and water was added to give the appropriate water/rice ratio (Table 1). The rice was cooked with or without prior soaking (Table 1) in a Breville RC19XL ten-cup rice cooker-steamer (randomly selected from five used) to completion. Samples were taken from the rice cookers as described by Champagne *et al.*[9]

Table 1. Rice cooker and pan preparation methods for rice samples

Variety	Rice cooker methods: Wash (no. times)	Water/rice	Soak time (min)	Mean cook time (min) to cooker shut-off
KDML 105	2	1.5 : 1.0	0	20
PTT1	2	1.5 : 1.0	0	21
Zhongzheyou 1	3	1.35 : 1.0	15	18
Guodao 6	3	1.5 : 1.0	15	19
IR 64[a]	3	1.4 : 1.0	10	20
IRRI 1132[a]	3	1.4 : 1.0	10	20
Koshihikari	2	1.4 : 1.0	30	18
Koshiibuki	2	1.4 : 1.0	30	19
Langi	2	1.4 : 1.0	0	22
Pelde	2	1.4 : 1.0	0	22
Aromatic se2	2	1.7 : 1.0	20	22
Charleston Gold	2	1.7 : 1.0	20	23
Dellmati	2	1.7 : 1.0	20	25
Dellrose	2	1.7 : 1.0	20	26
Jasmine 85	2	1.7 : 1.0	20	23
Jazzman	2	1.7 : 1.0	20	24
JES	2	1.7 : 1.0	20	24
Sierra	2	1.7 : 1.0	20	25

Variety	Pan methods: Wash (no. times)	Water/rice	Soak time (min)	Mean cook time (min)
Super Basmati	3	Excess	30	17
Basmati 385	3	Excess	30	20
Samba Mahsuri	3	Excess	30	21
Swarna	3	Excess	30	21
Hashemi[b]	5	Excess	120	11[a]
Khazar[b]	5	Excess	120	10[a]
BR IRGA 417 (2008)	3	Complete evaporation (2 : 1)	0	16
BR IRGA 417 (2009)	3	Complete evaporation (2 : 1)	0	15
BRS Jacana	3	Complete evaporation (2 : 1)	0	17
BRS Primavera	3	Complete evaporation (2 : 1)	0	15

[a] Drained in strainer 15 min after washing.
[b] Rice samples were steamed on top of hot oil for 10 min following cooking.

Samples prepared using pan methods with excess water

Portions (600 g) were washed three to five times (Table 1). The rice was added to three times as much water (w/w), soaked (Table 1) and boiled until the grains had no opaque centre when pressed between two pieces of glass. The excess water was drained off. The drained samples from Iran (Hashemi and Khazar) were mounded on top of hot Crisco vegetable oil (18.9 ml), the pan was covered and the rice was steamed for 10 min.

Samples prepared using pan methods with complete evaporation

Portions (three cups ≈600 g) were washed three times and then pan fried in Crisco vegetable oil for 5 min. Six cups of boiling water were added and, after it reached the boil again, the rice was allowed to simmer until the water evaporated. Rice samples were cooled to room temperature for colour analysis.

Colour

Colour was recorded as tristimulus L^*, a^* and b^* values using a HunterLab MiniScan XE Plus Diffuse LAV M072096 colorimeter (Reston, VA, USA) with a 1 inch diameter specimen port. The standard observer was 10° and the illuminant was D65 (afternoon daylight). The system was standardised using the white and black tiles provided by HunterLab for this instrument. Colour was measured in triplicate on the raw rice and on the cooked rice each of the two times it was prepared: $L^* =$ black (0) to white (100); $a^* =$ green ($-a^*$) to red ($+a^*$); $b^* =$ blue ($-b^*$) to yellow ($+b^*$); chroma $C^* = (a^{*2} + b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle $= \tan^{-1}(b^*/a^*)$, position in colour space.

Statistical analysis

In order to assess relationships among protein, amylose and the five colour variables (L^*, a^*, b^*, C^* and hue angle), mean values were computed and used in the analyses. Analyses were run separately for raw, cooked and difference between raw and cooked rice data sets. Linear relationships among the colour variables, protein and amylose were characterised using Pearson correlation coefficients. Multivariate multiple regression, which allows for multiple response (dependent) variables, was used to test for significant effects of protein and amylose on the five colour variables collectively for raw and cooked rice. Multivariate multiple regression was also used to test for significant effects of protein, amylose and raw colour variables on the five cooked colour variables collectively. Tests for parameter differences across the five colour variables were also performed. Wilk's lambda test statistics were used to test for significance of model fit. Diagnostic tests were performed to check assumptions and model fit. Additionally, multivariable regression models were used to test for significant effects of protein, amylose and raw colour variables on cooked colour variables in two subsets of the rice cultivars. One subset included only rice samples prepared using a rice cooker, while the other subset included only rice samples grown in the USA. Results were considered significant at the 0.05 level. All analyses were performed using SAS® Version 9.2 (SAS Institute Inc., Cary, NC, USA).

RESULTS AND DISCUSSION

Rice cultivars

The diverse rice cultivar set consisted of 20 premium rice cultivars from nine countries representing non-aromatic and aromatic (jasmine and basmati) types, along with eight aromatic rice cultivars grown in the USA consisting of jasmine, basmati and della types. Amylose and protein contents of the set ranged from 133 to 255 g kg^{-1} and from 59 to 112 g kg^{-1} respectively (Table 2). Amylose content was higher in the cultivars grown in Arkansas (mean 193 g kg^{-1}) than in those grown in Texas (mean 176 g kg^{-1}), with the exception of Sierra for which a significant location difference was not present. Conversely, protein content was lower in all cultivars grown in Arkansas (mean 77 g kg^{-1}) than in those grown in Texas (mean 87 g kg^{-1}).

Table 2. Composition of rice cultivar set for colour analyses

Cultivar	Type	Amylose (g kg^{-1})	Protein (g kg^{-1})
Zhongzheyou	Non-aromatic	155	72
Guodao 6	Non-aromatic	185	74
Koshihikari	Non-aromatic	181	59
Koshiibuki	Non-aromatic	161	59
IR 64	Non-aromatic	217	82
IRRI 1132	Non-aromatic	170	87
KDML 105	Aromatic/jasmine	240	104
PTT1	Aromatic/jasmine	242	86
Pelde	Non-aromatic	157	69
Langi	Non-aromatic	166	80
IRGA 417 (2008)	Non-aromatic	212	70
Jacana	Non-aromatic	214	74
IRGA 417 (2009)	Non-aromatic	249	87
Primavera	Non-aromatic	255	75
Super Basmati	Aromatic/basmati	246	77
Basmati 385	Aromatic/basmati	235	112
Sambha Mahsuri	Non-aromatic/slender	234	80
Swarna	Non-aromatic/slender	249	82
Hashemi	Aromatic/basmati type	213	103
Khazar	Aromatic/basmati type	222	92
Aromatic se2/AR	Aromatic/basmati type	195	85
Aromatic se2/TX	Aromatic/basmati type	163	91
Charleston Gold/AR	Aromatic/jasmine	202	91
Charleston Gold/TX	Aromatic/jasmine	184	104
Dellmati/AR	Aromatic/basmati type	203	92
Dellmati/TX	Aromatic/basmati type	193	96
Dellrose/AR	Aromatic/della type	207	69
Dellrose/TX	Aromatic/della type	198	77
Jasmine 85/AR	Aromatic/jasmine	169	67
Jasmine 85/TX	Aromatic/jasmine	134	78
Jazzman/AR	Aromatic/jasmine	158	62
Jazzman/TX	Aromatic/jasmine	133	77
JES/AR	Aromatic/jasmine	158	82
JES/TX	Aromatic/jasmine	145	92
Sierra/AR	Aromatic/della type	255	70
Sierra/TX	Aromatic/della type	255	81

Colour of raw and cooked rice

Tables 3 and 4 list the measured L^*, a^* and b^* values and the calculated C^* values and hue angles respectively of the raw and cooked rice samples. L^*, a measure of brightness, ranged from 70.4 to 80.2 in the raw rice. The range of L^* values for the cooked rice samples was narrower (75.2 to 80.3), with 15 cultivars showing an increase and five a decrease in L^* with cooking. The amount of green/red colour (a^*) in the raw cultivars varied markedly from −1.0 to 1.0, but the variation in the cooked cultivars was smaller (−2.1 to −1.5). The colour became greener with cooking. The value of b^* ranged from 10.0 to 15.3 in the raw samples and from

Table 3. Tristimulus L^*, a^* and b^* values for colour measured using a HunterLab MiniScan XE Plus Diffuse LAV M072096 colorimeter[a]

	L^*			a^*			b^*		
Cultivar	Raw	Cooked	Diff.[b]	Raw	Cooked	Diff.[b]	Raw	Cooked	Diff.[b]
Zhongzheyou	79.6	77.1	2.5	−0.6	−1.8	1.2	11.1	6.0	5.1
Guodao 6	75.8	76.7	−0.9	−0.5	−1.9	1.4	11.3	5.6	5.7
Koshihikari	77.1	75.9	1.2	−0.8	−2.1	1.3	12.8	5.1	7.7
Koshiibuki	74.7	75.6	−0.9	−1.0	−2.1	1.1	12.9	5.0	7.9
IR 64	78.1	77.3	0.8	−0.6	−1.8	1.2	12.3	5.2	7.1
IRRI 1132	79.1	79.3	−0.2	0.2	−1.7	1.9	13.8	7.0	6.8
KDML 105	77.3	79.0	−1.7	−1.0	−2.0	1.0	11.6	5.0	6.6
PTT1	71.9	78.0	−6.1	0.0	−1.9	1.9	13.4	5.2	8.2
Pelde	75.8	77.7	−1.9	−0.6	−2.0	1.4	13.5	5.8	7.7
Langi	77.1	77.9	−0.8	−0.8	−2.1	1.3	12.5	6.0	6.5
IRGA 417 (2008)	76.0	76.8	−0.8	−1.0	−1.8	0.8	10.0	2.4	7.6
Jacana	75.4	76.7	−1.3	−0.5	−1.9	1.4	11.5	3.2	8.3
IRGA 417 (2009)	73.3	76.4	−3.1	−0.5	−1.7	1.2	11.7	3.3	8.4
Primavera	73.2	78.9	−5.7	−1.0	−1.8	0.8	12.5	4.8	7.7
Super Basmati	77.1	78.1	−1.0	−0.3	−1.8	1.5	12.9	3.9	9.0
Basmati 385	76.8	76.2	0.6	1.0	−1.8	2.8	15.3	2.7	12.6
Sambha Mahsuri	76.3	78.6	−2.3	0.2	−1.7	1.9	15.3	4.8	10.5
Swarna	78.6	76.9	1.7	−0.4	−1.7	1.3	13.6	3.4	10.2
Hashemi	77.7	79.1	−1.4	0.1	−1.8	1.9	15.3	5.4	9.9
Khazar	78.1	79.1	−1.0	0.1	−1.8	1.9	15.0	5.0	10.0
Aromatic se2/AR	76.6	78.1	−1.5	−0.2	−1.8	1.6	13.0	5.2	7.8
Aromatic se2/TX	80.2	80.3	−0.1	−0.3	−1.7	1.4	12.2	4.4	7.8
Charleston Gold/AR	76.3	77.3	−1.0	−0.6	−1.7	1.1	11.7	5.4	6.3
Charleston Gold/TX	74.9	77.1	−2.2	−0.3	−1.6	1.3	12.4	6.2	6.2
Dellmati/AR	75.3	78.7	−3.4	−0.3	−1.7	1.4	12.3	5.5	6.8
Dellmati/TX	74.3	79.6	−5.3	−0.2	−1.8	1.6	12.8	5.9	6.9
Dellrose/AR	76.0	78.8	−2.8	−0.7	−1.9	1.2	11.7	4.5	7.2
Dellrose/TX	74.8	78.9	−4.1	−0.4	−1.9	1.5	12.6	5.1	7.5
Jasmine 85/AR	71.5	76.9	−5.4	−0.2	−1.8	1.6	11.8	4.7	7.1
Jasmine 85/TX	73.2	78.0	−4.8	−0.1	−1.6	1.5	11.6	4.0	7.6
Jazzman/AR	73.0	78.3	−5.3	−0.5	−2.1	1.6	12.0	5.1	6.9
Jazzman/TX	73.4	78.5	−5.1	−0.7	−2.0	1.3	12.1	6.2	5.9
JES/AR	72.2	75.8	−3.6	−0.4	−1.8	1.4	12.0	5.3	6.7
JES/TX	70.4	75.2	−4.8	−0.2	−1.5	1.3	11.9	5.8	6.1
Sierra/AR	76.5	76.9	−0.4	−0.3	−2.0	1.7	12.5	4.2	8.3
Sierra/TX	76.8	78.1	−1.3	−0.5	−1.9	1.4	12.5	4.4	8.1

[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness.
[b] Difference = raw value − cooked value.

2.4 to 7.0 in the cooked samples. Thus b^* decreased from raw to cooked, moving from yellow towards blue.

The samples with the largest decreases in b^* with cooking were Sambha Mahsuri, Swarna, Super Basmati, Basmati 385, Hashemi and Khazar, with differences between raw and cooked rice of 10.5, 10.2, 9.0, 12.6, 9.9 and 10.0 respectively. These varieties are basmati types or similar to the basmati type with slender, elongating grains. In contrast, the US-grown basmati types Aromatic se2 and Dellmati had smaller decreases in b^* (7.8 and 6.9 respectively). In addition to growing region, the US-grown basmati-type cultivars differed from the international basmati/basmati-type cultivars in preparation method (rice cooker *versus* excess water respectively). Yellow pigments that leach into the cooking water when excess water is used would be lost when the rice is drained, whereas all pigments would be reabsorbed by the rice when prepared using a rice cooker. Thus, when rice is cooked in excess water, the b^* values would be expected to be smaller and hence the b^* difference between raw and cooked larger compared with b^* values and differences of rice prepared in a rice cooker. The mean difference in b^* between raw and cooked rice for rice prepared in a rice cooker or with complete evaporation (Brazilian rice samples) was 7.2 and for rice prepared with excess water was 10.4. Likewise, the mean difference in a^* between raw and cooked rice was larger for rice cooked in excess water than for rice cooked in a rice cooker or with complete evaporation (1.9 *vs* 1.5 respectively). These suppositions concerning the effects of cooking method on colour variable measurements were confirmed by cooking each of two samples (commercial basmati and long-grain non-aromatic rice) in a rice cooker and with excess water in duplicate. As shown in Table 5, rice cooked in excess water was whiter (larger L^*), more green (smaller

Table 4. C^* values and hue angles calculated from tristimulus a^* and b^* values measured using a HunterLab MiniScan XE Plus Diffuse LAV M072096 colorimeter[a]

	C^*			Hue angle		
Cultivar	Raw	Cooked	Diff.[b]	Raw	Cooked	Diff.[b]
Zhongzheyou	11.2	6.1	5.1	93.0	108.0	−15.0
Guodao 6	11.3	6.2	5.1	92.6	106.4	−13.8
Koshihikari	12.8	5.5	7.3	93.7	112.7	−19.0
Koshiibuki	13.0	5.5	7.5	94.3	112.9	−18.6
IR 64	12.3	5.6	6.7	92.9	109.7	−16.8
IRRI 1132	13.8	7.2	6.6	89.2	103.8	−14.6
KDML 105	11.6	5.4	6.2	94.7	112.2	−17.5
PTT1	13.4	5.5	7.9	89.9	110.0	−20.1
Pelde	13.5	6.2	7.3	92.4	109.4	−17.0
Langi	12.6	6.3	6.3	93.5	109.0	−15.5
IRGA 417 (2008)	10.0	3.0	7.0	95.8	126.7	−30.9
Jacana	11.5	3.7	7.8	92.4	120.4	−28.0
IRGA 417 (2009)	11.7	3.7	8.0	92.3	116.8	−24.5
Primavera	12.5	5.1	7.4	94.4	110.4	−16.0
Super Basmati	12.9	4.3	8.6	91.5	114.8	−23.3
Basmati 385	15.4	3.2	12.2	86.5	123.6	−37.1
Sambha Mahsuri	15.3	5.1	10.2	89.2	109.7	−20.5
Swarna	13.7	3.9	9.8	91.7	117.2	−25.5
Hashemi	15.3	5.7	9.6	89.5	108.8	−19.3
Khazar	15.0	5.3	9.7	89.6	109.9	−20.3
Aromatic se2/AR	13.0	5.5	7.5	91.0	109.0	−18.0
Aromatic se2/TX	12.2	4.7	7.5	91.3	110.9	−19.6
Charleston Gold/AR	11.7	5.7	6.0	92.8	107.6	−14.8
Charleston Gold/TX	12.4	6.4	6.0	91.4	104.3	−12.9
Dellmati/AR	13.2	5.7	7.5	91.5	107.4	−15.9
Dellmati/TX	12.8	6.1	6.7	90.8	106.6	−15.8
Dellrose/AR	11.7	4.9	6.8	93.3	113.0	−19.7
Dellrose/TX	12.6	5.4	7.2	91.9	110.8	−18.9
Jasmine 85/AR	11.8	5.1	6.7	91.1	111.0	−19.9
Jasmine 85/TX	11.6	4.3	7.3	90.5	112.6	−22.1
Jazzman/AR	12.0	5.5	6.5	92.6	112.6	−20.0
Jazzman/TX	12.2	6.5	5.7	93.1	108.3	−15.2
JES/AR	12.0	5.6	6.4	92.0	108.8	−16.8
JES/TX	11.9	6.0	5.9	90.8	104.9	−14.1
Sierra/AR	12.5	4.7	7.8	91.6	115.3	−23.7
Sierra/TX	12.6	4.8	7.8	92.1	113.7	−21.6

[a] $C^* = (a^{*2} + b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle = $\tan^{-1}(b^*/a^*)$, position in colour space.
[b] Difference = raw value − cooked value.

Table 5. Comparison of mean colour measurements on basmati and long-grain non-aromatic rice cooked in rice cooker or excess water[a]

Colour variable	Raw	Rice cooker	Excess water
L^*	75.7	78.1	78.8
a^*	0.2	−1.5	−1.7
b^*	14.5	6.5	5.1
C^*	14.5	6.7	5.4
Hue angle	89.4	103.6	108.4

All row values were significantly different from one another at the 0.05 level.
[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness; chroma $C^* = (a^{*2}+b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle = $\tan^{-1}(b^*/a^*)$, position in colour space.

a^*), less yellow (smaller b^*), less vivid or more grey (smaller C^*) and had a larger hue angle than that cooked in a rice cooker.

C^* decreased upon cooking, indicating that the rice lost vividness or became more grey (Table 4). The largest decrease in C^* was seen with Basmati 385, followed by Samba Mahsuri, Swarna, Khazar, Hashemi and Super Basmati (range 8.6 to 12.2). These decreases in C^* were primarily due to the decreases observed in b^*, as discussed above. In addition to loss of vividness, the colour changed from yellow to greenish yellow. On average, hue angle increased after cooking for the 28 rice samples by 19.5°. Basmati 385 had the largest increase at 37.1°.

In addition to leaching of pigments into the water during cooking, the differences in colour between raw and cooked rice have been explained as resulting from the diffusion of pigments from the rice surface to the inner layers, leading to lower yellow and red in the cooked rice kernels.[10,11] In support of this explanation, water uptake during cooking was observed to increase with degree of milling, resulting in lower pigment concentrations (lower levels of red and yellow) on the surface of cooked rice.[10,11]

Relationships among colour variables, protein and amylose

Linear relationships among the colour variables, protein and amylose were characterised using correlation coefficients (Table 6). In the raw rice samples, L^* was not significantly correlated with the other four colour variables. However, a^*, b^*, C^* and hue angle were significantly correlated with each other. Positive relationships were present among a^*, b^* and C^*, whereas hue angle was negatively related to a^*, b^* and C^*. In the cooked rice samples, neither L^* nor a^* was significantly correlated with each other or the other three colour variables. However, b^*, C^* and hue angle were significantly correlated with each other in the same direction as was found in the raw rice samples. In the raw rice samples, neither protein nor amylose was significantly correlated with the colour variables. Protein had moderate positive relationships with L^* and a^* but no association with b^*, C^* and hue angle in the cooked samples. Cooking resulted in amylose having a moderate positive association with a^*, negative associations with b^* and C^* and no association with L^* and hue angle.

Linear relationships were also examined among the raw and cooked colour variables (Table 7). In the raw samples, a^* and hue angle had moderate positive and negative relationships respectively with a^* in the cooked rice. L^*, b^* and C^* of the raw rice were significantly correlated with L^* of the cooked rice, but the relationships were weak. The only other significant correlation between raw and cooked colour variables was L^* of raw rice with a^* of cooked rice, but the relationship was again weak.

Predicting colour of raw and cooked rice with protein and amylose contents in combination

Multivariate multiple regression was used to determine if protein and amylose contents together could be used to predict the colour of raw and cooked rice. For the raw rice data the model with amylose and protein was not significant, indicating that these components were unable to explain a significant portion of the

Table 6. Linear relationships among colour variables, protein and amylose in raw and cooked rice[a,b]

		Raw		Cooked	
Variable 1	Variable 2	*r*	*P*	*r*	*P*
L^*	a^*	0.06	0.7385	0.02	0.9059
	b^*	0.26	0.1222	0.23	0.1727
	C^*	0.26	0.1199	0.22	0.1882
	Hue angle	−0.04	0.7956	−0.28	0.1038
a^*	b^*	0.69	<0.0001	−0.08	0.6509
	C^*	0.68	<0.0001	−0.13	0.4566
	Hue angle	−0.99	<0.0001	−0.18	0.2928
b^*	C^*	1.00	<0.0001	1.00	<0.0001
	Hue angle	−0.72	<0.0001	−0.94	<0.0001
C^*	Hue angle	−0.71	<0.0001	−0.92	<0.0001
Protein	L^*	−0.09	0.5821	0.36	0.0322
	a^*	0.27	0.1055	0.42	0.0100
	b^*	0.29	0.0869	0.01	0.9433
	C^*	0.29	0.0875	−0.01	0.9524
	Hue angle	−0.26	0.1295	−0.12	0.4723
Amylose	L^*	0.10	0.5765	−0.15	0.3985
	a^*	0.11	0.5187	0.38	0.0207
	b^*	0.19	0.2563	−0.34	0.0448
	C^*	0.20	0.2513	−0.35	0.0368
	Hue angle	−0.07	0.6734	0.28	0.0992

[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness; chroma $C^* = (a^{*2}+b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle $= \tan^{-1}(b^*/a^*)$, position in colour space.
[b] *r*, Pearson correlation coefficient; *P*, *P* value.

variability in the colour variables. For the cooked rice data, protein had a significant positive effect on L^* and a^* when accounting for amylose in the model (Table 8). Conversely, amylose had a significant negative effect on b^* and C^* when accounting for protein in the model.

The model using amylose and protein to predict rice colour was also run using the differences in the colour variables (raw minus cooked) as the dependent variables (Table 8). Protein had a significant negative effect on L^* when accounting for amylose in the model. Amylose had significant positive effects on b^* and C^* when accounting for protein in the model.

The low R^2 values listed in Table 8 indicate that protein and amylose in combination were not sufficient to predict variability in the colour of cooked rice or the difference in colour between raw and cooked rice.

Table 7. Linear relationships among raw and cooked colour variables[a,b]

		Cooked				
Raw		L^*	a^*	b^*	C^*	Hue angle
L^*	*r*	0.2038	−0.1360	−0.0145	−0.0041	0.0893
	P	0.0028	0.0475	0.8330	0.9528	0.1943
a^*	*r*	0.1001	0.4602	−0.0501	−0.0721	−0.0490
	P	0.1429	<0.0001	0.4673	0.2949	0.4769
b^*	*r*	0.2118	0.0336	0.0730	0.0689	−0.0908
	P	0.0019	0.6259	0.2892	0.3168	0.1867
C^*	*r*	0.2103	0.0291	0.0699	0.0662	−0.0858
	P	0.0020	0.6726	0.3097	0.3362	0.2124
Hue angle	*r*	−0.1203	−0.4405	−0.0172	0.0060	0.1281
	P	0.0797	<0.0001	0.0835	0.9302	0.0619

[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness; chroma $C^* = (a^{*2}+b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle $= \tan^{-1}(b^*/a^*)$, position in colour space.
[b] *r*, Pearson correlation coefficient; *P*, *P* value.

Table 8. Multivariate multiple regression using protein and amylose contents together to predict colour of cooked rice and change in colour upon cooking of international and US rice samples[a,b]

		Independent					
		Protein		Amylose			
Dependent	*I*	*b*	*P*(*t*)	*b*	*P*(*t*)	R^2	*P*(*F*)
Cooked							
L^*	76.02	0.41	0.0138	−0.08	0.1294	0.19	0.0325
a^*	−2.42	0.04	0.0310	0.01	0.0648	0.26	0.0068
b^*	6.19	0.08	0.5391	−0.10	0.0386	0.12	0.1138
C^*	6.62	0.06	0.6208	−0.09	0.0345	0.13	0.1032
Hue angle	109.21	−0.81	0.2268	0.44	0.0579	0.12	0.1249
Difference							
L^*	−0.04	−0.65	0.0399	0.1642	0.1201	0.15	0.0703
a^*	1.28	0.04	0.4355	−0.007	0.6838	0.02	0.7176
b^*	3.82	0.13	0.5176	0.1422	0.0433	0.15	0.0655
C^*	3.17	0.18	0.3621	0.1379	0.0412	0.17	0.0453
Hue angle	−14.31	0.45	0.5074	−0.447	0.0606	0.10	0.1650

[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness; chroma $C^* = (a^{*2}+b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle $= \tan^{-1}(b^*/a^*)$, position in colour space.
[b] *I*, intercept; *b*, parameter estimate (model coefficient); *P*(*t*), *P* value for *t* test; *P*(*F*), *P* value for Wilk's lambda *F* test.

Predicting colour of cooked rice with raw rice colour variables in combination with protein and amylose contents

A model was run regressing the cooked rice colour variables onto protein, amylose and the raw rice colour variables to determine if the colour of raw rice in combination with its protein and amylose contents can be used to better predict the colour of cooked rice (Table 9). Amylose and the raw rice colour variables b^* and C^* were not significant and hence were dropped from the model. In this model, protein had a significant positive effect on L^* (cooked) when accounting for a^* (raw) and hue angle (raw). The raw color variable a^* had significant negative effects on b^* (cooked) and C^* (cooked) and a significant positive effect on hue angle (cooked) when accounting for the other variables in the model. The raw colour variable hue angle had significant negative effects on b^* (cooked) and C^* (cooked) and a significant positive effect on hue angle (cooked). The values of R^2 were larger when the raw colour variables were included in the model with amylose

Table 9. Multivariate multiple linear regression using raw colour variables in conjunction with protein and amylose to predict cooked rice colour using international and US rice set. Only significant independent variable results are reported[a,b]

		Independent									
		Protein		L^* (raw)		a^* (raw)		Hue angle (raw)			
Dependent	*I*	*b*	*P*(*t*)	*b*	*P*(*t*)	*b*	*P*(*t*)	*b*	*P*(*t*)	R^2	*P*(*F*)
Cooked											
L^*	160.66	0.40	0.0150	0.19	0.0312	−5.02	0.1571	−1.11	0.1500	0.28	0.0307
a^*	−5.34	0.04	0.0653	−0.01	0.4614	0.41	0.3969	0.04	0.6362	0.34	0.0095
b^*	179.90	0.07	0.6054	0.01	0.8616	−9.07	0.0039	−1.96	0.0042	0.24	0.0679
C^*	163.63	0.05	0.6846	0.01	0.8296	−8.27	0.0048	−1.77	0.0053	0.23	0.0797
Hue angle	−934.52	−0.70	0.2389	0.04	0.8934	52.59	0.0003	11.63	0.0002	0.37	0.0051

[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness; chroma $C^* = (a^{*2} + b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle $= \tan^{-1}(b^*/a^*)$, position in colour space.
[b] *I*, intercept; *b*, parameter estimate (model coefficient); *P*(*t*), *P* value for *t* test; *P*(*F*), *P* value for Wilk's lambda *F* test.

Table 10. Multivariable linear regression using raw colour variables in conjunction with protein and amylose to predict cooked rice colour using international and US rice samples prepared in rice cookers. Only the a^* model was significant for the cooked colour variables. Protein was not significant at the 0.05 level but was included in the model owing to its effect on the other independent variables (i.e. its removal caused other variables to be non-significant)[a,b]

		Independent															
		Protein		Amylose		L^* (raw)		a^* (raw)		b^* (raw)		C^* (raw)		Hue angle (raw)			
Dependent	*I*	*b*	*P*(*t*)	*b*	*P*(*t*)	*b*	*P*(*t*)	*b*	*P*(*t*)	*b*	*P*(*t*)	*b*	*P*(*t*)	*b*	*P*(*t*)	R^2	*P*(*F*)
Cooked																	
a^*	77.54	0.03	0.0834	0.03	<0.0001	0.02	0.0192	−2.87	0.0072	−14.49	0.0066	14.21	0.0071	−0.86	0.0018	0.89	<0.0001

[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness; chroma $C^* = (a^{*2} + b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle $= \tan^{-1}(b^*/a^*)$, position in colour space.
[b] *I*, intercept; *b*, parameter estimate (model coefficient); *P*(*t*), *P* value for *t* test; *P*(*F*), *P* value for Wilk's lambda *F* test.

and protein; however, the amount of variability accounted for by these variables was still insufficient to reliably predict cooked rice colour.

Cooking method can affect the colour of the cooked rice, as discussed above and shown in Table 5. Therefore models (Table 10) were run regressing the cooked rice colour variables onto protein, amylose and the raw colour variables for just the rice prepared in rice cookers (Table 1). Only the a^* (cooked) model was significant for this subset of rice samples. Although protein was not significant at the 0.05 level, it was kept in the model owing to its effect on the other variables (i.e. removal resulted in loss of significance for the other variables). Amylose, L^* (raw) and C^* (raw) had significant positive effects on a^* (cooked), while a^* (raw), b^* (raw) and hue angle (raw) had significant negative effects. The proportion of variability (0.89) explained in the a^* (cooked) model was sufficient to allow for useful predictions, as can be seen by the predicted values and associated 95% confidence intervals (CIs) given in Table 11.

The postharvest handling conditions for the US-grown rice were the same for all rice samples, thus controlling for three factors (drying, degree of milling, storage) that can affect the colour of the rice.[10,11] Although the subset of US rice samples was small, models were run regressing the cooked rice colour variables onto protein, amylose and the raw colour variables (Table 12). Only the L^* (cooked) model was not statistically significant, indicating that the L^* value for cooked rice could not be predicted using protein, amylose and raw colour variables. In these models, amylose had significant positive effects on a^* (cooked), b^* (cooked) and C^* (cooked) and a significant negative effect on hue angle (cooked). L^* (raw) and a^* (raw) had significant negative effects on b^* (cooked) and C^* (cooked), while b^* (raw) had a significant negative effect on a^* (cooked). Hue angle (raw) had significant negative effects on a^* (cooked), b^* (cooked) and C^* (cooked). Only the proportion of variability (0.80) explained in the a^* (cooked) model was sufficient to allow for useful predictions.

CONCLUSIONS

This research details the linear relationships among the tristimulus (L^*, a^*, b^*) and calculated (C^*, hue angle) colour variables of raw and cooked rice and their protein and amylose contents using diverse rice samples. Protein and amylose contents were not significantly correlated with the measured or calculated colour measurements for raw rice. Protein and amylose showed moderate, significant associations with L^* and a^* and a^*, b^* and C^* respectively for cooked rice. Only a^* and hue angle of raw rice showed moderate, significant associations with a cooked rice colour variable, and that variable was a^*.

Table 11. Observed and predicted a^* values with 95% confidence interval (CI)[a]

Cultivar	a^* value Observed	Predicted	95% CI Lower	Upper
Aust Langi	−2.0	−1.9	−2.1	−1.8
Aust Pelde	−2.0	−2.0	−2.2	−1.9
China Guodao 6	−1.8	−1.8	−2.0	−1.7
China ZhongZheyou	−1.9	−1.9	−2.0	−1.7
Japan Koshibuki	−2.1	−2.2	−2.4	−2.0
Japan Koshihikari	−2.1	−2.1	−2.2	−1.9
Philip IR 64	−1.8	−1.8	−2.0	−1.7
Philip IRRI 132	−1.7	−1.7	−1.9	−1.5
Thai KDML 105	−2.0	−2.1	−2.3	−2.0
Thai PTT 1	−1.9	−1.9	−2.0	−1.7
Aromatic se2/AR	−1.8	−1.8	−2.0	−1.7
Aromatic se2/TX	−1.7	−1.7	−1.9	−1.6
Charleston Gold/AR	−1.7	−1.7	−1.9	−1.6
Charleston Gold/TX	−1.6	−1.6	−1.8	−1.5
Dellmati/AR	−1.7	−1.8	−1.9	−1.6
Dellmati/TX	−1.8	−1.8	−1.9	−1.6
Dellrose/AR	−1.9	−1.9	−2.1	−1.7
Dellrose/TX	−1.9	−1.9	−2.0	−1.7
Jasmine 85/AR	−1.8	−1.8	−1.9	−1.6
Jasmine 85/TX	−1.6	−1.6	−1.8	−1.4
Jazzman/AR	−2.1	−2.0	−2.2	−1.9
Jazzman/TX	−2.0	−2.1	−2.2	−1.9
JES/AR	−1.8	−1.8	−2.0	−1.7
JES/TX	−1.5	−1.6	−1.8	−1.4
Sierra/AR	−2.0	−1.9	−2.1	−1.8
Sierra/TX	−1.9	−2.0	−2.2	−1.9

[a] a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness.

A useful tool for the rice industry would be one that can predict cooked rice colour from raw rice. Based on models generated in this research using a set of diverse rice samples, amylose and protein in combination would not be adequate for predicting cooked rice colour or the difference between cooked and raw rice colour. Improvement in the predictive abilities of the models was obtained when raw rice colour measurements were included with amylose and protein contents in the regression. However, only the colour variable a^* of cooked rice could be predicted with high enough precision to be useful, and this was only for modelling using samples cooked in the same manner (rice cooker). The colour variable a^*, as with b^*, is a coordinate that indirectly reflects hue angle and C^* but is difficult to interpret separately.[12] Thus being able to predict this variable in cooked rice is likely of limited value. McGuire[12] argues that more useful measures of colour are hue angle and C^*. The predictive abilities of all models for hue angle were poor. In our research, only the model that used samples where postharvest handling conditions were controlled (US-grown rice) was able to predict C^*, and then with only moderate ability. L^*, a measure of brightness/whiteness, was not predicted well by any of the models. Improvements in the predictive ability of models using raw colour variables, protein and amylose for cooked colour variables may possibly be gleaned with larger sample sets, but controlling for conditions that affect colour (e.g. cooking method) will likely have to be taken into consideration in the model development.

ACKNOWLEDGEMENTS

Ken'ichi Ohtsubo (Niigata University, Niigata, Japan), Supanee Jongdee (Ubon Ratchathani Rice Research Center, Ubon Ratchathani, Thailand), Lihong Xie (China National Rice Research Institute, Hangzhou, China), Priscila Bassinello (Embrapa, Goias, Brazil), Adoracion Resurreccion (Grain Quality, Nutrition and Postharvest Centre, International Rice Research Institute, Metro Manila, Philippines), Rauf Ahmad (National Agricultural Research Centre, Islamabad, Pakistan), Fatemah Habibi (Rice Research Institute of Iran, Rasht, Iran), Russell Reinke (Yanco Agricultural Institute, Yanco, Australia) and Anna McClung (ARS Dale Bumpers National Rice Research Center, Stuttgart, AR, USA) are acknowledged for contributing rice varieties for this study. Ming Chen (ARS Rice Research Unit, Beaumont, TX, USA), Rolfe Bryant (ARS Dale Bumpers National Rice Research Center, Stuttgart, AR, USA) and Kim Daigle (ARS Southern Regional Research Center, New Orleans, LA, USA) are thanked for contributing protein and amylose content data.

Table 12. Multivariable linear regression using raw colour variables in conjunction with protein and amylose to predict cooked rice colour using US rice samples. Only significant models for cooked colour variables are reported, and only significant independent variable results are reported[a,b]

Dependent	*I*	Amylose *b*	Amylose *P*(*t*)	L^* (raw) *b*	L^* (raw) *P*(*t*)	a^* (raw) *b*	a^* (raw) *P*(*t*)	b^* (raw) *b*	b^* (raw) *P*(*t*)	Hue angle (raw) *b*	Hue angle (raw) *P*(*t*)	R^2	*P*(*F*)
Cooked													
L^*	NS	NS		NS		NS		NS		NS		0.54	0.3481
a^*	13.70	0.02	0.0016	NS		NS		−0.15	0.0171	−0.15	0.0001	0.80	0.0002
b^*	419.86	0.13	0.0037	−0.14	0.0213	−22.86	0.0247	NS		−4.52	0.0269	0.65	0.0136
C^*	412.57	0.11	0.0043	−0.13	0.0177	−22.65	0.0169	NS		−4.44	0.0193	0.66	0.0117
Hue angle	120.13	−0.56	0.0072	NS		NS		NS		NS		0.41	0.0072

[a] L^* is measure of brightness from black (0) to white (100); a^* describes red/green colour, with positive a^* values redness and negative a^* values greenness; b^* describes yellow/blue colour, with positive b^* values yellowness and negative b^* values blueness; chroma $C^* = (a^{*2} + b^{*2})^{1/2}$, colour intensity (vivid *versus* dull); hue angle $= \tan^{-1}(b^*/a^*)$, position in colour space.
[b] *I*, intercept; *b*, parameter estimate (model coefficient); *P*(*t*), *P* value for *t* test; *P*(*F*), *P* value for Wilk's lambda *F* test; NS, not significant in model.

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